REPOR DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL REPORT - 15 Aug 92 - 14 Apr 95

4. TITLE AND SUBTITLE
Low-Resistance, High-Power-Efficiency Vertical Cavity Microlasers

5. FUNDING NUMBERS
61102F
2305/DS

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AFOSR-TR-96
0340

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
F49620-92-C-0053

11. SUPPLEMENTARY NOTES

19960701 031

12a. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

13. ABSTRACT (Maximum 200 words)
The purpose of this project was to improve the total power efficiency of vertical-cavity microlasers to further the commercialization of large arrays of semiconductor lasers integrated on single chips. Vertical-cavity surface-emitting lasers are tiny semiconductor lasers, typically about 10 um in diameter, whose optical cavities and electrical injection schemes are radically different from conventional "edge-emitting" semiconductor lasers. The VCSSEL geometry emits high-quality beams perpendicular to the face of the chip, rather than out the edge of the chip, and can bse readily fabricated in one- and two-dimensional arrays. A preliminary demonstration of the modulation-doped approach was made. The result was a record-low threshold voltage of 1.7 volts for VCSELs. Previously, VCSELs required a minimum of about 2.5 volts for thresholed or had very high current thresholds. This demonstration destroyed the then-widely-held micsconception that VCSELs inherently were high resistance and high-voltage devices.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

DTIC QUALITY INSPECTED 1

Low-Resistance, High-Power-Efficiency Vertical Cavity Microlasers

Sponsored by
Defense Advanced Research Projects Agency
ARPA Order No. 8678
Monitored by AFOSR Under Contract No. F49620-92-C-0053

Final Technical Report
20 May, 1996

(1) ARPA Order 8678
(2) Program Code 2D10
(3) Vixel Corporation
(formerly Photonics Research Inc.)
(4) Effective Date: 15 August 1992
(5) Expiration Date: 20 May, 1996
(6) Contract Dollars: $452,522
(7) Contract No. F49620-92-C-0053
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Low-Resistance, High-Power-Efficiency Vertical Cavity Microlasers

Final Technical Report

1. Report Summary

Introduction

The purpose of this project was to improve the total power efficiency of vertical-cavity microlasers to further the commercialization of large arrays of semiconductor lasers integrated on single chips. Vertical-cavity surface-emitting lasers are tiny semiconductor lasers, typically about 10 μm in diameter, whose optical cavities and electrical injection schemes are radically different from conventional "edge-emitting" semiconductor lasers. In the past few years since this program initiation, VCSELs have seen explosive growth, not just in research labs, but also in commercial products. Vixel Corporation was the first company in the world to commercialize VCSEL products, the first commercial application being in laser printing. Vixel and other companies are presently directing intensive activity toward commercializing parallel-fiber optical interconnects. Vixel's P-Vixel Link is a 4-channel interconnect that transfers an aggregate 5Gb/sec. The VCSEL geometry emits high-quality beams perpendicular to the face of the chip, rather than out the edge of the chip, and can be readily fabricated in one- and two-dimensional arrays. VCSELs have many other advantages over edge-emitters which have become common knowledge in the laser community. Early overview articles of VCSEL properties can be found, for example, in Jewell, 1991a, 1991b, 1992a, 1992b.

Central to the attainment of high power efficiency (wallplug efficiency) is the simultaneous minimization of: 1) electrical resistance, 2) optical absorption in the cavity, and 3) threshold current. Most approaches to improving one of these characteristics does so only at the expense of another. For example, decreasing the resistance by increasing the doping levels in the semiconductors will simultaneously increase the optical absorption. The basis of this project is to develop VCSEL designs which circumvent the "resistance-absorption tradeoff." The most elegant design approach and the one which promises the highest efficiency modulates the doping concentrations, making it higher in regions where the standing-wave optical intensity is low and lower throughout the rest of the structure. This approach was outlined in the proposal. Another feature required for high efficiency is confinement of current to the central portion of the VCSEL, where optical intensity is highest.

Not addressed in this program was the control of diffractive losses in the cavity. Diffractive losses have been greatly reduced (by other groups) in the so-called "oxide VCSELs" in which the oxide-defined current aperture also forms a crude intracavity "lens" which reduces the diffractive losses. The lowest-threshold oxide VCSEL used an undoped top mirror and an intracavity p-type contact, similar to the p-type current injection investigated in this program. The current injection schemes investigated here are sufficiently general that they can be implemented in oxide VCSELs as well as ion implanted VCSELs. Indeed the most efficient oxide VCSELs will probably use the current injection schemes reported here.

The primary conclusions from this program are as follows: 1) Despite the successes in lower-resistance p-doped mirrors, their optoelectronic performance is still inferior to modulation-doped intracavity contacts; 2) all the advances in performance made possible by oxide VCSELs will be furthered by modulation-doped intracavity contacts; and 3) the fabrication of intracavity contacts is significantly more difficult than fabrication of standard through-mirror contacts.

Results

A bullet list of selected accomplishments and activities in the contract period is presented in chronological order as follows:

- Calculated optical and electrical characteristics of modulation-doped VCSEL structures for maximum doping levels of $\leq 10^{19}$ cm^{-3} as limited by beryllium as the dopant. Selected an 8-layer structure as optimal for the constraint on concentration.
- Purchased DW-2000 software package for the layout of photolithographic masks.
- Designed "stratified-p-layer" vertical-cavity lasers for emission at 740, 850 and 980 nm with doping concentrations $\leq 10^{19}$ cm^{-3} as limited by beryllium as the dopant.
- Developed process follower for the fabrication of vertical-cavity lasers having shallow implantation depths and dielectric mirrors.
- Designed full set of masks according to the process follower and had the masks fabricated.
- Demonstrated 8x8 array of 725 nm vertical-cavity lasers (Photonics Spectra, Nov. '92 issue, p.126).
- Filed U.S. Patent Application serial number 07/978,391 "Optical Beam Delivery System," filing date 18 November 1992. This case was split into 3 cases by the Patent Office. One case issued on June 7, 1994 as U.S. Patent No. 5,319,496. Another case has been allowed by the Patent Office (i.e. it will issue soon), and the third case is still pending.
- Filed U.S. Patent Application serial number 07/994,976 "Vertical Cavity Surface-Emitting Laser with Expanded Cavity," filing date 22 December 1992. This case issued on March 15, 1994 as U.S. Patent No. 5,295,147.
- Designed new "hybrid mirror" lasers, whose top mirror is partially semiconductor and partly dielectric, for 780 nm and 850 nm emission.
- Had a hybrid mirror wafer grown. Tested the wafer through reflectance and photoluminescense spectra, which verified the growth quality.
- Re-evaluated potential performance of VCSELs using improved low-resistance p-mirrors.
- Designed 3 versions of new-generation "stratified-p" VCSELs having carbon as the dopant.
- Designed new process followers and mask sets for the newer stratified-p VCSELs.
- Evaluated the thickness tolerances of the top dielectric mirrors.
- Fabricated the newer stratified-p VCSELs.
- Tested the new VCSELs, achieving sub-mA thresholds.
- Evaluated problems in the new VCSELs and made recommendations for improvement.

Soon after submission of the proposal, a preliminary demonstration of the modulation-doped approach was made through a collaboration between PRI and Bellcore. The result was a record-low threshold voltage of 1.7 volts for VCSELs [Jewell, 1992a; Scherer, 1992]. Previously, VCSELs required a minimum of about 2.5 volts for threshold or had very high current thresholds. This demonstration destroyed the then-widely-held misconception that VCSELs inherently were high-resistance and high-voltage devices. The significance of this difference is better appreciated by comparing these voltages to the bandgap energy of the active material, about 1.45 volts, below which essentially no current flows. The "additional" voltages required above bandgap were then 0.25 volts for the new devices compared to greater than 1 volt in previous devices. ~~The results validated our proposed approach to fabricating low-resistance VCSELs. The specific resistance (resistance x area) was nearly as low as in highly-developed edge-emitters.~~ High power efficiency was not achieved in this early demonstration.

Early in the contract period, we demonstrated an 8x8 array of quasi-visible, 725-nm-emitting VCSELs which used the proposed approach. A color photograph of the LASE-ARRAY™, which appeared in Photonics Spectra, is presented in this report (Fig. 1).

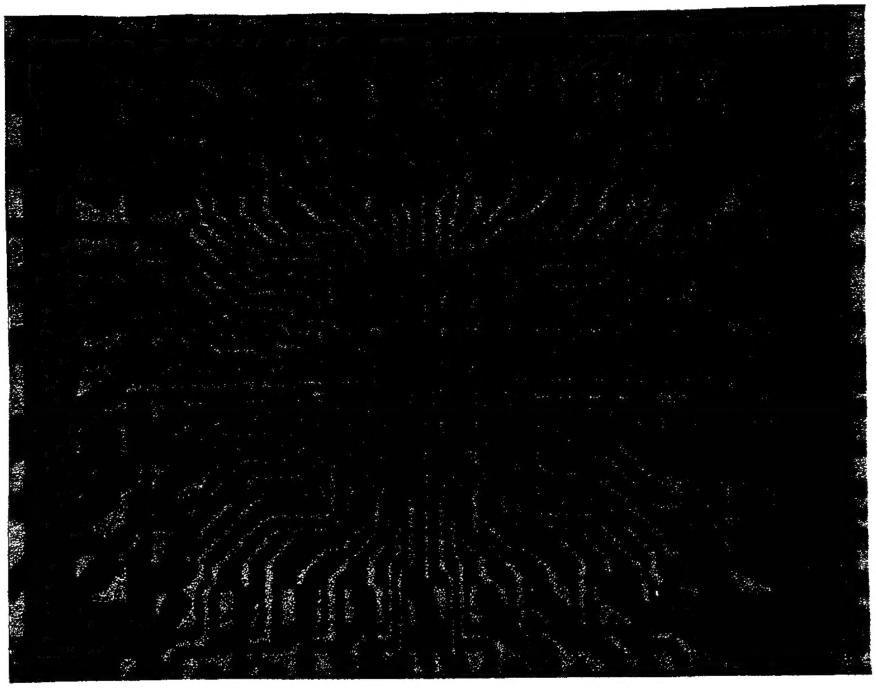


Fig. 1. Photomicrograph of a partially-activated 8x8 LASE-ARRAY™ emitting at 725 nm.

More detailed calculations have been carried out to predict and optimize the performances of VCSELs. The calculations include recently-reported improvements in p-type mirror design and improvements made to the design of the bottom, n-doped side of the VCSEL. Our experimental results and calculations concluded that the wallplug efficiencies in VCSELs can approach the high levels of 40-50 % attained in edge-emitters. This conclusion was eventually verified, albeit by other groups and through oxide-VCSEL structures.

Epitaxial designs and process followers were developed for the manufacture of 3 versions of high-efficiency VCSELs. All were similar in structure to the modulation-doped VCSEL illustrated in Figure 2 below. Photolithographic masks to accomplish the fabrication processes were laid out and fabricated. The 3 versions of high-efficiency VCSELs were fabricated and tested. Some of them lased with slightly less than 1 mA current, compared to about 3-5 mA for our lowest-threshold conventional VCSELs. The lower current thresholds are attributed to decreased absorption losses in the cavity as predicted in the original proposal. There were problems however. The resistances and voltages were disappointing. This is attributed to poor ohmic contacts. Another problem is apparent leakage of current around the device periphery which is not well-explained.

2. VCSEL Design Approaches

Background

The VCSEL is a complex 3-dimensional structure whose optical requirements and electrical pumping geometry are very different from any previous electronic or optoelectronic device. For this reason, early VCSEL demonstrations involved simple designs and did not achieve high efficiency. The 40-50 % wallplug efficiencies in edge-emitters was achieved through many years of development, initially involving qualitative structural design changes and followed by

quantitative refinements. VCSELs are still in the qualitative improvement phase, although this phase is maturing following demonstrations of >50% wallplug efficiency in oxide VCSELs. One of the first requirements for high efficiency, low threshold current density, was achieved in VCSELs several years ago by fabricating cavities with high enough finesse to work with a few quantum wells or even a single quantum well [Jewell, 1989; Lee, 1989]. The lowest threshold early VCSELs used single quantum wells (SQW) [Geels, 1990], but had very low output power and efficiency. The low efficiency resulted from optical absorption in the doped semiconductor mirrors and from high electrical resistance. More recent high-efficiency VCSELs have used 3 quantum wells, but the trend is moving toward using 2 wells or 1 well. A SQW VCSEL offers the best chance for achieving ultimately high efficiency and it is most sensitive to optical absorption.

Modulation-Doped Design

We have designed modulation-doped VCSELs for emission at 740 nm, 850 nm and 980 nm. Early on, a wafer was grown and fabricated which showed lasing at 725 nm. Recently, devices lased at 850nm with 1mA current. More details on the results will be presented in Section 4.

In the modulation-doped VCSEL described in the proposal the current completely bypasses the top mirror through conductive layers which contribute negligibly to the reflectivity. It can be considered an extreme departure from the conventional design where current flows completely through the top mirror. Both designs are illustrated in Figure 2. The modulation-doped design thus bypasses the potential barrier structure inherent to the interfaces of a semiconductor mirror which causes the high resistance. The sheet resistance of the conductive layer must be sufficiently low that the transverse current flow does not have high resistance. For conventional doping levels, on the order of 10^{19} cm^{-3} or less, the conductive layer must be about 1 μm thick. A 1-μm-thick layer comprises about 8 half-wave periods of the modulation-doped structure. An optimized modulation-doped layer confines the high doping concentrations to regions in the minima of the standing wave intensity pattern as shown in Figure 2. To help confine the dopant to the low-intensity regions, our designs use a lower bandgap material in these regions, for example AlGaAs of a lower Al composition.

The top contact surface of the modulation-doped conductive layer can be placed either in a peak or in a trough of the standing waves. Either placement involves tradeoffs relating to the fact that the top surface forms the electrical contact. High doping is appropriate for the electrical contact, but it causes high absorption in the peak of the standing wave. Thus electrical contacting considerations favor placement of the top surface in the trough. However this has two optically-related disadvantages. First, more layers are required for the dielectric mirror due to the fact that the dielectrics must start with a high-index layer rather than low-index. This relation between the dielectric layers and the standing wave position is fundamental to the operation of thin film cavities. Second, it is more difficult to derive information about the thickness of the optical cavity. In the case where a peak of the standing waves occurs at the top surface, a weak cavity resonance occurs at the desired lasing wavelength, which is in the center of the reflectivity region of the mirrors. Departure of the resonance from the desired wavelength indicates an error in the thickness of the conductive layer which can be corrected for in the deposition of the dielectric mirrors (as demonstrated [Scherer, 1992]). When the top surface is in a trough of the standing waves, the lasing wavelength lies directly between cavity resonances, making it difficult to determine the optical thickness of the conductive layer. It is possible to bypass this tradeoff through shallow etching or diffusion. The epitaxial structure would be grown fully optimally for the optical characteristics, with low doping and the standing wave peak at the top surface. In fabrication, a shallow etch of about 600 Å would reach the high-doped layer suitable for electrical contacting outside the optical cavity region. In this way, both optical and electrical characteristics are optimum. The shallow etch could also be replaced by a shallow diffusion of appropriate p-type dopant, e.g. zinc.

This choice of placement for the contact layer forms the basis for the 3 designs which were fabricated and tested later in the contract. The design choices are: 1) place the contact layer

and the highest optical surface in a node of the standing waves; 2) place the contact layer and the highest optical surface in an anti-node of the standing waves; 3) place the contact layer in the standing wave node and the highest optical surface in an anti-node of the standing waves, the different placements being accomplished by etching down a few hundred Å to the contact surface.

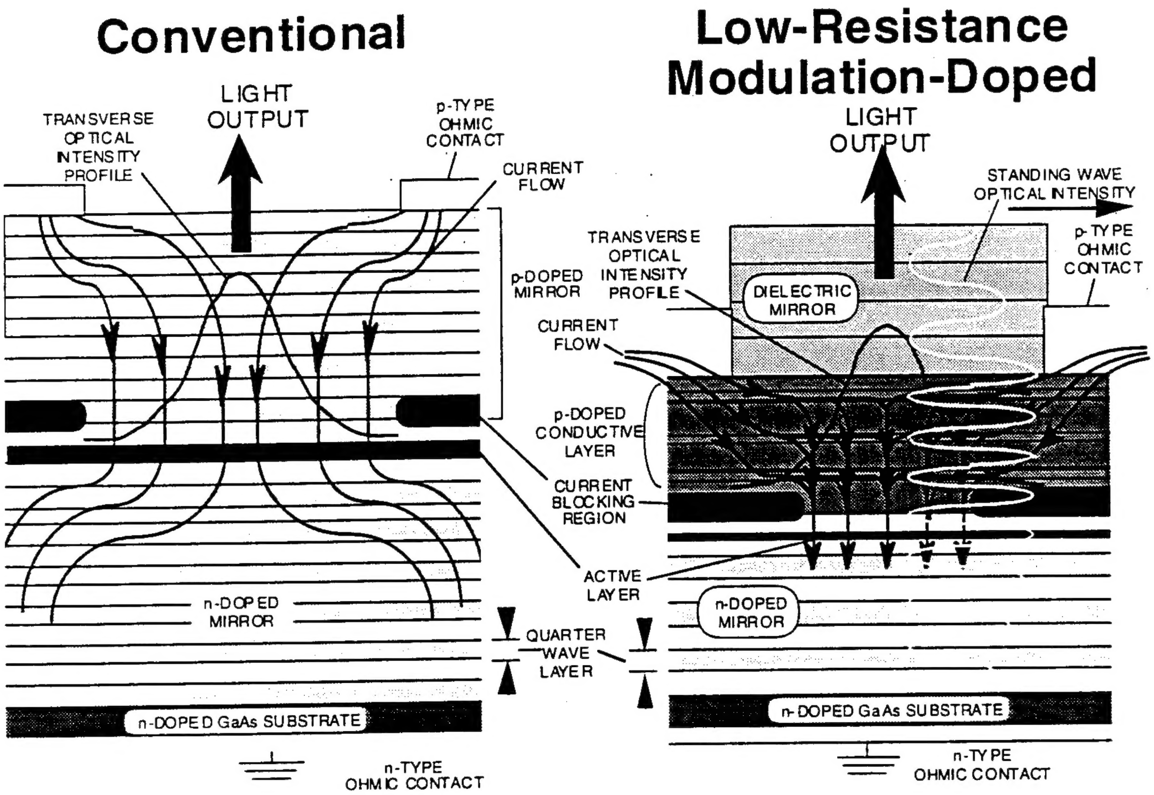


Figure 2. Comparison of electrical pumping geometries between "conventional" (left) and modulation-doped intra-cavity contacted (right) VCSELs.

Hybrid-Mirror Design

For moderate doping levels of 10^{19} cm^{-3} or less, the ~1 μm of material required for low transverse resistance is sufficiently thick that significant reflectivity may be obtained from it. We designed "hybrid-mirror" VCSELs for 780-nm, 850-nm, and 980-nm emission. Although the hybrid mirror VCSELs are not expected to have resistance/absorption losses as low as the modulation-doped VCSELs, the fabrication should be simpler owing to the greater precision in testing the epitaxial structure and the fewer required dielectric mirror layers. Furthermore the losses might eventually reach levels sufficiently low to be negligible anyway. Since the epitaxial portion of the hybrid mirror does not need to produce high reflectivity, its structure can be designed to accommodate current flow. For example, the component materials of the material can have less than 50% difference in aluminum concentration, greatly alleviating the well/barrier-induced high longitudinal resistance. We had a hybrid-mirror VCSEL wafer grown by our subcontractor Lockheed Missiles & Space Company. Other wafers from Lockheed exhibited very high resistances. We did not process this wafer.

New Low-Resistance P-Doped Mirrors

During the contract period, other groups have reported significant improvements in decreasing the resistance of p-type mirrors [Lear, 1992] by smoothly grading the aluminum composition between layers. Even with dopings of 1.5 x 10^{18} cm^{-3}, the current vs. voltage (I/V)

characteristics are linear, indicating the absence of well/barrier-induced resistance. Absorption losses are much lower than they are with conventional mirrors doped at 5×10^{18} cm^{-3}. The losses are fairly negligible for cavities having a 1% transmission output mirror (appropriate for 3-quantum-well active material), but still somewhat high for a higher-finesse cavity appropriate for SQW active region. The optical efficiencies for these two cases are included in Table 1, which compares a variety of designs, most of them the modulation-doped design.

<u>Continuity of the Three Basic Designs</u>

The three design approaches discussed above are by no means mutually exclusive. They could, in principle, all be combined into a single viable design. Smooth grading of aluminum concentration in the layer interfaces (low-resistance p-mirror) should be used in optimizing the hybrid-mirror design, since for the same resistance, a higher reflectivity could be obtained by utilizing larger differences in aluminum concentration. Modulation doping is utilized in our hybrid-mirror design and should also be used in smoothly-graded p-mirror designs.

<u>Confinement of Current to the Central Portion of the Cavity</u>

A design feature which is independent of the three design approaches discussed above is the importance of confining current flow to the central portion of the VCSEL cavity. Measurements of the optical intensity profile in VCSELs show the $1/e^2$ intensity diameter of the emitted beam to be about 1/2 the diameter of the electrical contact which forms the optical aperture. Thus, most of the optical intensity is in about 1/4 the area of the aperture. Pumping current outside this region produces carriers which are either largely lost to nonradiative recombination, or they help induce higher-order transverse modes which complicate use of the VCSELs in systems. This confinement, and the gaussian intensity profile, are illustrated in Fig. 2.

<u>Re-Calculated Performances of VCSEL Designs</u>

In Table 1 we present re-calculated performances of some of the VCSEL designs discussed above. This table has the same format as the table presented in the proposal, but there are important differences. First, the losses assumed for the n-doped mirror have been reduced from 0.0005 to 0.0001. This reduction is appropriate for advanced VCSEL designs which incorporate modulation doping and/or smoothly-varying aluminum composition in the n-doped bottom mirror. Second, in the multiple-layer modulation-doped structures absorption due to the lightly-doped regions is included. A doping concentration of 1×10^{17} cm^{-3} was assumed for these regions, which still produces non-negligible absorption due to their thickness and placement in the intensity peaks of the standing waves. Third, some designs which are not considered for this project have been deleted, while two new ones are included: the smoothly-graded low-resistance p-mirror design and the 8-period modulation-doped structure with maximum doping of 1×10^{19} cm^{-3}.

material	thickness	ρ (μΩ-cm)	α (cm-1)	A	η (.990)	η (.998)	Z (Ω)
"old standard" (5E18)	(0.5 μm)	NA	50	.0026	.79	.43	NA
"new p-type" (1.5E18)	(0.5 μm)	NA	10	.00085	.92	.70	
p++(1E20)	500 Å	1,000	500	.00027	.97	.88	16
p++(1E21)	300 Å	333	1,500	.00023	.98	.90	8
p+ (1E19) 4 layers	600 Å each	5,000	100	.00039	.96	.84	16
p+ (1E19) 8 layers	600 Å each	5,000	100	.00068	.94	.75	8
p++(1E20) 4 layers	250 Å each	1,000	500	.00026	.97	.88	8
p++(1E21) 4 layers	150 Å each	333	1,500	.00024	.98	.89	4

Table 1. Calculated values of single-pass absorption A, differential quantum efficiency η for mirror reflectivities 0.99 and 0.998 (appropriate for four- and single-quantum-well active layers, respectively), and p-side spreading resistance Z, for designs incorporating conductive layers of resistivity ρ, and absorptivity α. The "new p-type" design incorporates a p-doped mirror with smoothly-graded interfaces.

3. Experimental Results

725 nm VCSELs

We demonstrated an 8x8 array of VCSELs emitting at 725 nm wavelength at room temperature. A photograph of the array, with several elements activated, is shown in Fig. 1. Low film sensitivity at 725 nm greatly reduced the apparent brightness of the VCSELs in the photograph. Thresholds of 21 mA with 100 ns pulses were recorded for 15-μm diameter devices. The design, which avoids current flow through the top mirror, is based on one we reported earlier [Jewell, 1992; Scherer, 1992], but with higher aluminum concentrations for emission at the shorter wavelengths. Molecular beam epitaxy (MBE) was used to grow 32 pairs of n-doped $Al_{0.3}Ga_{0.7}As/GaAs$ bottom mirror layers, the active region containing 500 Å of $(GaAs)_4(AlAs)_1$ superlattice, and a 1-μm-thick p-doped heterostructure top conductive layer. 11 1/2 pairs of alternating SiO_2/Si_3N_4 layers, deposited by reactive sputtering, formed a high-reflectivity mirror which completed the laser cavity. As previously, individual laser elements were defined by ion milling of mesas through the p-n junction, followed by planarization with SiO_2 to define the current path. Then, Au-Zn p-contacts were deposited around the mesa tops and alloyed for current injection. Finally, another ion milling step was used to isolate individual contacts.

Light at 720-740 nm is generated by the superlattice active region and the output emits through the annular p-contact. GaAs/AlAs superlattices are reported to be superior to alloy AlGaAs in luminescent efficiency. The p-side resistance is reduced by beryllium modulation-doping in the top of the cavity. In this device the p-conductive region comprised alternating layers of $Al_{0.3}Ga_{0.7}As$ and $Al_{0.5}Ga_{0.5}As$. The heterostructure serves to equalize the current density throughout the microlaser active region, rather than allowing it to crowd preferentially around the outer edges. Furthermore, the lower-Al-concentration layers contained higher Be-doping concentrations and they were centered at the minimum-intensity regions of the standing waves in the optical cavity; thus the maximum absorptivity overlapped the minimum light intensity. Poor adhesion of the SiO_2 insulating layer to the high-aluminum-content sidewalls prevented annealing of the ohmic contacts, thus the current vs. voltage characteristic shows a soft turn-on. The specific resistance is $\sim 2\times10^{-4}$ Ωcm^2, or about 2.5 times higher than for our previous low-resistance VCSELs [Jewell, 1992; Scherer, 1992], but still far lower than conventional VCSELs with annealed contacts. The low resistance design allows the devices to handle pulsed currents of over 50 mA through 15-μm diameters (~25 kA/cm^2). This high-current capability is obviously important for high-power applications.

Since the contact diameter is smaller than that of the pumped region, most of the light intensity is within an area about one-sixth that of the region being pumped. The poor overlap is partly responsible for the low quantum efficiency indicated by the light vs. current plot of Fig. 4. It can be avoided through use of a buried implant having a smaller diameter than the contact, resulting in not only increased quantum efficiency, but single-transverse-mode emission. Other likely causes are current leakage through the active region due to heating caused by the high currents employed, and non-optimized reflectivity in the top mirror.

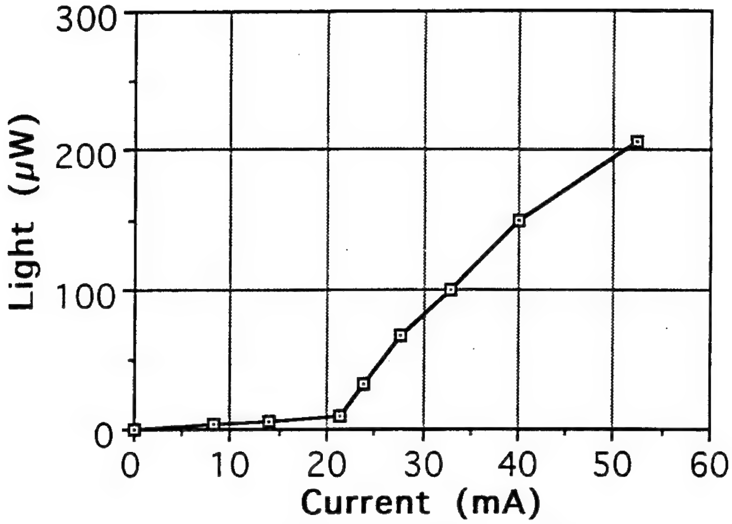


Figure 3. Light vs. current for the 10-μm-diameter, 725-nm-emitting VCSEL.

850 nm Hybrid-Mirror Wafer

We designed, and had grown, a hybrid-mirror VCSEL wafer by Lockheed. We performed process development to verify key steps in the process follower outlined in Section 3 of the first Annual Report. The wafer exhibited a photoluminescense peak at about 843 nm, about what is desired for temperature-insensitive operation when the emission is at 850nm. The full structure is specified in the first Annual Report of this contract.

Advanced Modulation-Doped Intracavity-Contacted VCSELs

The choice of placement for the contact layer in a modulation-doped intracavity-contacted VCSEL forms the basis for 3 designs which we fabricated and tested in the later part of the contract. The design choices are: 1) place the contact layer and the highest optical surface in a node of the standing waves; 2) place the contact layer and the highest optical surface in an anti-node of the standing waves; 3) place the contact layer in the standing wave node and the highest optical surface in an anti-node of the standing waves, the different placements being accomplished by etching down a few hundred Å to the contact surface. The 3 designs are shown pictorially in Figure 4.

The epitaxial designs for the 3 VCSELs were identical except for the very top layers. A portion of Vixel's "standard" VCSEL mask set was modified to confine current flow to various diameters. The diameter of the ohmic contact was 8μm and the mask features defining the current aperture had diameters of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0 and 8.5 μm. VCSELs with the highest optical surface of the semiconductor portion lying at an optical antinode, (b) and (c) in Figure 4, required only 9 periods of SiO_2/Si_3N_4, starting with SiO_2, to achieve the desired 99.5% reflectivity of the top mirror. These designs are referred to optically as the "antinode" versions. To achieve the same reflectivity, the "node" version, Figure 4(a), requires 11.5 periods starting with Si_3N_4.

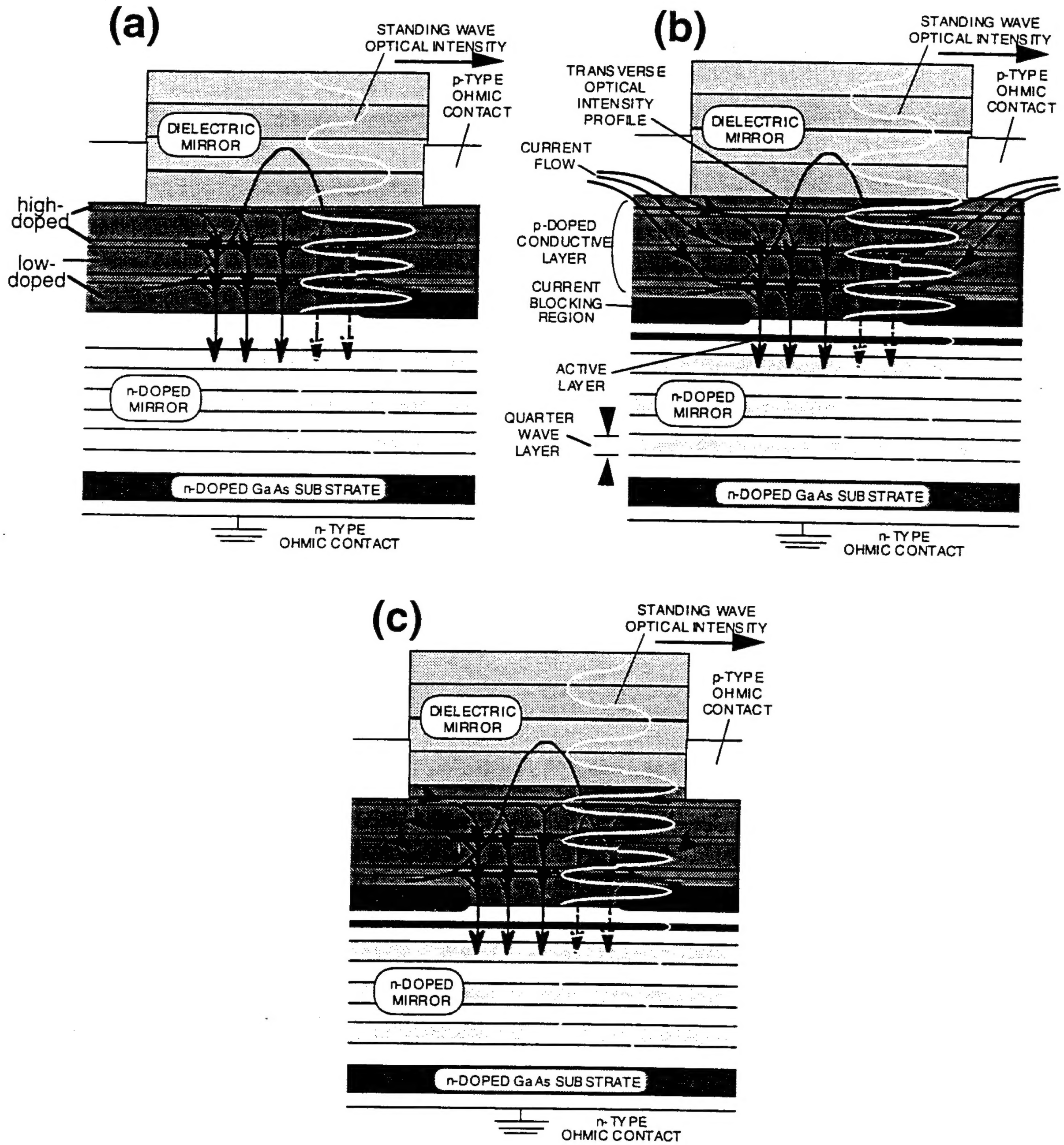
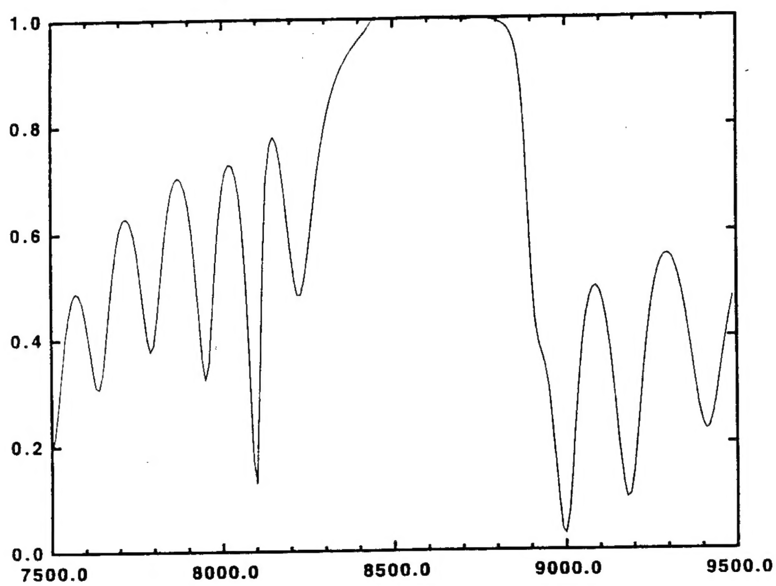


Figure 4. Schematic illustrations of the 3 forms of modulation-doped intracavity-contacted VCSELs designed and fabricated in this contract.

Test results were obtained from 2 wafers, the "node" version of Figure 4(a) and the "etch" version of Figure 4(c). The "node" version produced the best results. The reflectivity spectra for the simulated design and for the as-grown wafer are shown in Figure 5. The usual large dip in reflectance is not present because in the node version of the as-grown wafer, the center of the high-reflectance region lies directly <u>between</u> two cavity resonances. This is why the node version wafer spectra are more difficult to interpret. The agreement is remarkable, especially knowing that the "ripples" on either side of the high-reflectance band are very sensitive to small changes in the layer structure. The measured reflectance additionally shows two dips in the high-reflectance region. These dips are usually seen in the reflectance spectra of "node version" wafers and the dips are

exactly what would be expected from excitonic absorption in the active material. The incident light makes a double pass through the active material as it reflects off the bottom mirror, which enhances their effect. The active material had 3 GaAs quantum wells, nominally 80Å thick. The four quadrants of the wafer received four different dosages of the proton implant to confine the current flow, 5E12, 1E13, 3E13 and 1E14 cm^{-2}. The highest dosage regions showed the best performances and had good isolation from one device to another. 12 1/2 periods of the SiO_2/Si_3N_4 dielectric mirror were deposited, providing a calculated 99.77% reflectivity for the top mirror.



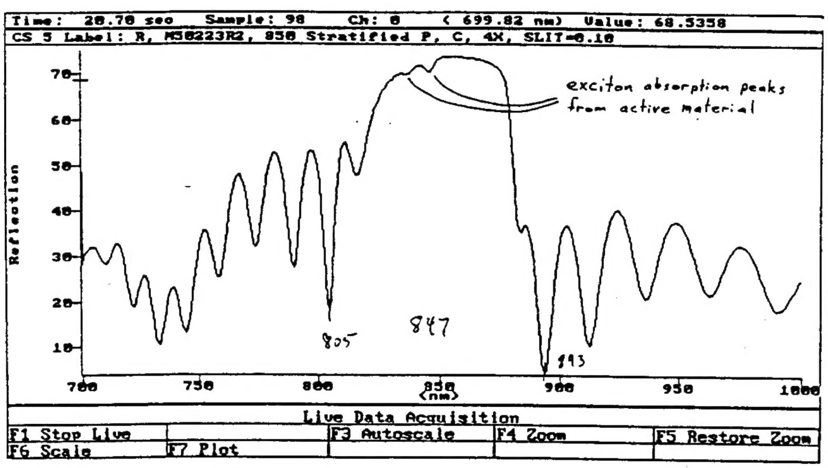


Figure 5. Calculated (top) and measured (bottom) reflectance spectra of the "node version" modulation-doped intracavity-contacted VCSEL, absent any of the dielectric top mirror layers.

Initial testing revealed lasing thresholds of 1.2mA current and 1.8 Volts in one of the "standard" devices. Later probing of the "parameter space" devices yielded current thresholds slightly less than 1.0mA in devices with the 5.5μm current apertures. The quantum efficiency was poor however, partly due to the very high reflectivity of the output (top) mirror. The device with 1.2mA threshold had a maximum output power of only 0.5mW and that was at 7.6mA current with 2.9 volts.

Attempts were made to etch away one period of the top mirror to improve the external quantum efficiency, however these attempts were not successful. It is possible that improved annealing of the ohmic contacts would lower the resistance and yield significantly higher efficiency.

The "etch version" of Figure 4(c) was also fabricated, however the isolation from device to device was very poor. Hence there was excessive current leakage and none of the devices lased.

Section 4. U.S. Patents

Four U.S. Patent applications have been filed which are related to this contract: two parent applications, one divisional application and one continuation-in-part application. Two U.S. Patents have issued, one application has been allowed by the U.S. Patent Office, and one is still pending. Foreign patent applications have also been filed for one of the patents.

- U.S. Patent Application serial number 07/978,391 "Optical Beam Delivery System," filing date 18 November 1992. This case was split into 3 cases by the Patent Office. One case issued on June 7, 1994 as U.S. Patent No. 5,319,496.

- U.S. Patent Application serial number 07/994,976 "Vertical Cavity Surface-Emitting Laser with Expanded Cavity," filing date 22 December 1992. This case issued on March 15, 1994 as U.S. Patent No. 5,295,147. Foreign patent applications have also been filed.

- U.S. Patent Application serial number 08/194,019 "Optical Beam Delivery System," filing date 9 February 1994, as a divisional of U.S. Patent No. 5,319,496. This application has been allowed by the U.S. Patent Office, i.e. it will soon issue as a patent.

- U.S. Patent Application serial number 08/198,290 "Optical Beam Combiner," filing date 18 February 1994, as a continuation-in-part of U.S. Patent No. 5,319,496. This application is still pending.

Section 5. Related Publications

J.L. Jewell, A. Scherer, M. Walther, J.P. Harbison, and L.T. Florez, "Low-Voltage-Threshold Microlasers," IEEE Lasers and Electro-Optics Society 1992 Annual Meeting, Boston, MA, Nov. 16-19, pp. 544-545, paper DLTA13.3, (1992).

R.P. Bryan, G.R. Olbright, J.L. Jewell, R.P. Schneider, and S. Swirhun, "Vertical-Cavity Microlaser Smart Pixels," IEEE Lasers and Electro-Optics Society 1992 Annual Meeting, Boston, MA, Nov. 16-19, pp. 596-597, paper EOS/OTA2.5, (1992).

A. Scherer, J.L. Jewell, M. Walther, J.P. Harbison, and L.T. Florez, "Fabrication of Low-Threshold-Voltage Microlasers," Electron. Lett., **28**, pp. 1224-1226 (1992).

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R.P. Bryan, J.L. Jewell, G.R. Olbright, and W.S. Fu, "Micro-Optic and Microelectronic Integrated Packaging of Vertical Cavity Laser Arrays," Publications of the SPIE for OE/LASE '93, Los Angeles, CA, Jan. 1993.

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A. Scherer, J.L. Jewell, J.P. Harbison, and L.T. Florez, "Fabrication of Microlaser Arrays", OE/LASE '94, January 1994, Invited.

Section 6. References

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Jewell, J.L. and G.R. Olbright, "Surface-Emitting Lasers Emerge from the Laboratory," Laser Focus World, vol. 28, p. 217, May (1992b).

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